Future FNAL Neutrino Scattering Experiments

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Why?

- On our roadmap to understanding neutrino masses and mixings…

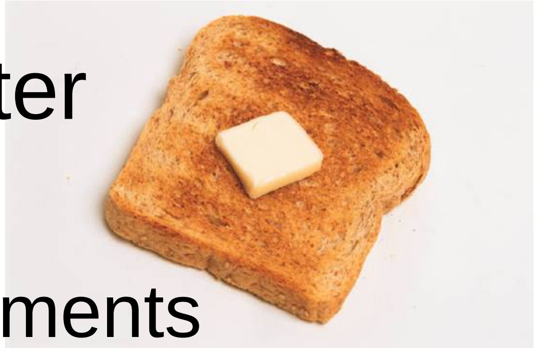
the physics of neutrino scattering
will not set the course through the parameter space of possible future neutrino beams

– barring an enormous surprise, of course ☺

Why? (cont'd)

- "Because it's there." A.k.a., exploration
  - the high rates required by oscillation experiments imply orders(!) of magnitude increases in flux at near detectors

- Because it's our bread and butter
  - Great thesis topics for students
  - Engineering for oscillation experiments



- Because it unifies communities
  - think of JLab with neutrinos
  - NP/HEP collaborations

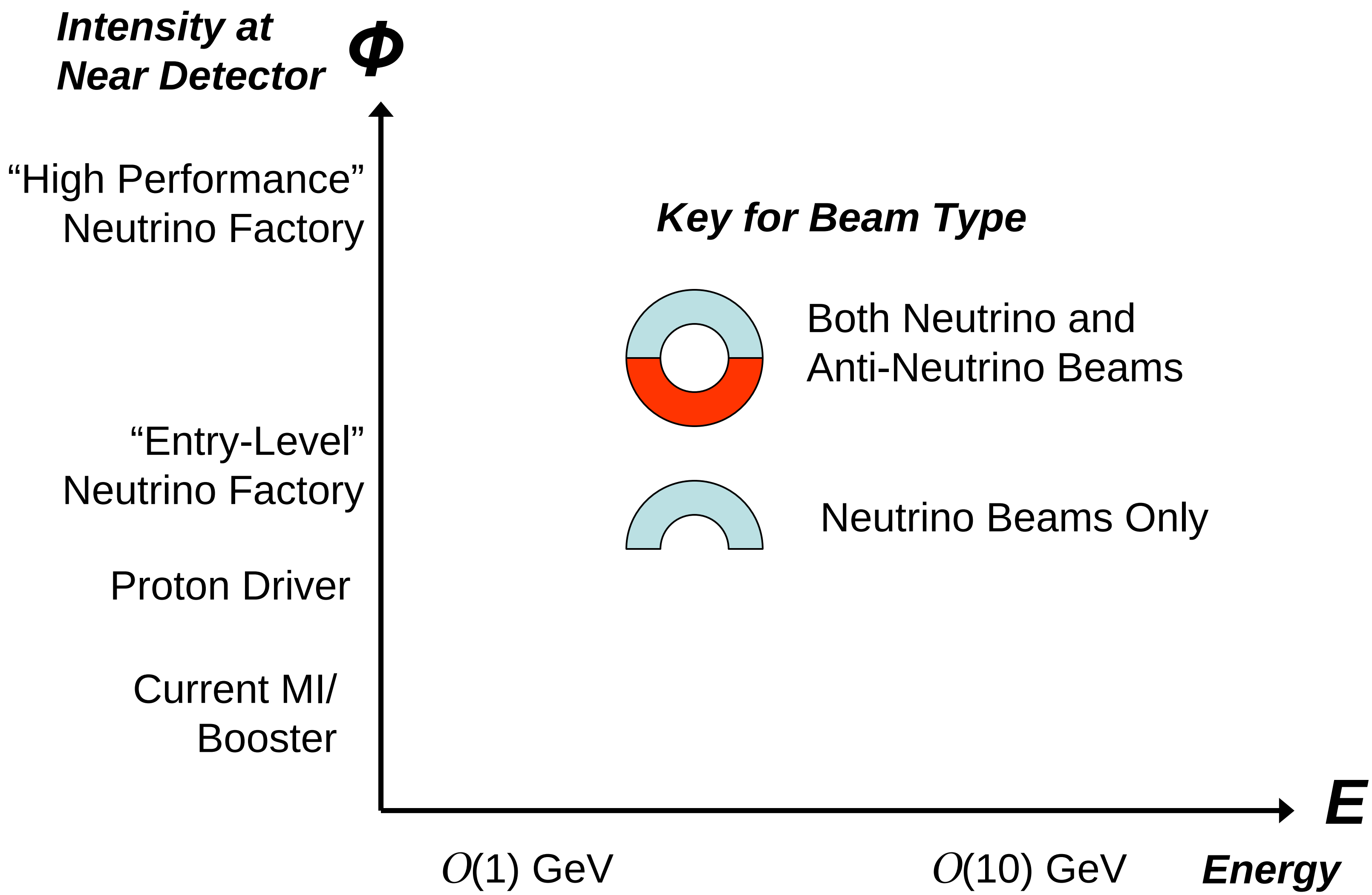
What?

- Near detectors associated with oscillation experiments
  - direct measurements of fluxes, backgrounds and signal cross-sections
- QCD and Nucleon Structure
  - for its own sake
  - for cross-section model-building to for oscillation measurements
- More speculative topics
  - BSM Neutrino Interactions, Rare Processes, etc.

How?

- Current FNAL beams
  - MiniBooNE, NuMI
- Future Beams that could be built
  - Conventional beams
    - Proton driver, Main Injector, TeVatron FT(?)
  - Neutrino Factory Beams
- Planned and Future Detectors
  - MiniBooNE
  - MINOS Near Detector
  - MINERνA, FineSe, Off-Axis Near Detector
  - Light (H_2, D_2) targets, ν Factory near detectors

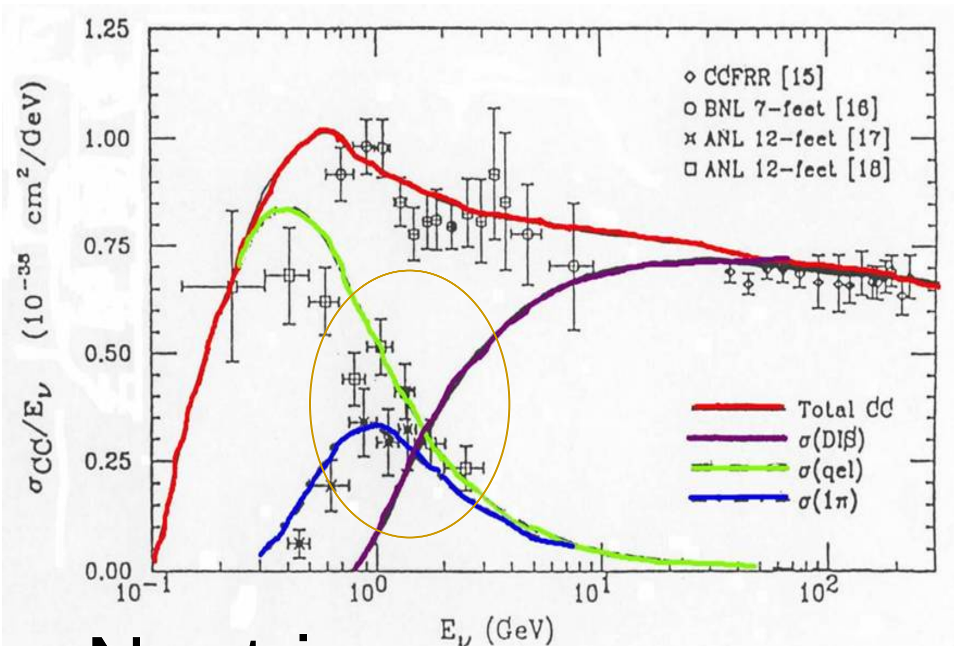
Characterizing Beams



An Example of the Program:

A Roadmap for Studies of QCD and Nucleon Structure

Neutrino Cross-Sections



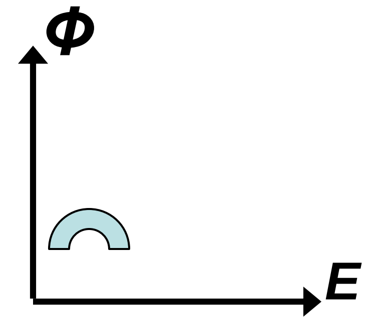
Neutrino cross-sections vs. Energy

- Quasi-Elastic / Elastic
  - $\nu_\mu n \rightarrow \mu^- p$ (x =1, W=M_p)
- Resonance
  - $\nu_\mu p \rightarrow \mu^- \pi p$ (low Q^2, W)
- Coherent
  - $\nu_\mu N \rightarrow \mu^- \pi^+ (\nu \pi^0) N$
- Deep Inelastic
  - $\nu_\mu N \rightarrow \mu^- X$ (high Q^2, W)

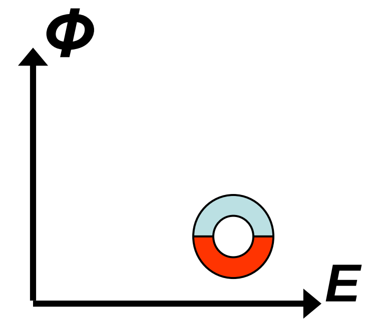
Knowledge of exclusive final states, differential distributions in 1-10 GeV region is sketchy…

Example: Roadmap for QCD and Nucleon Structure

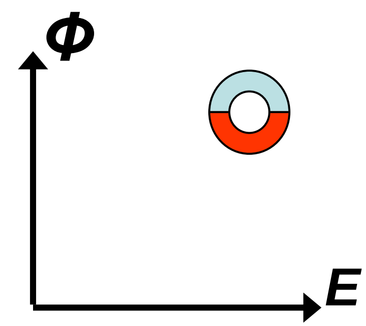
- Low Energies (few GeV or below)
  - (Quasi)elastic processes
  - Coherent pion production
  - Modeling the “Resonance Region”



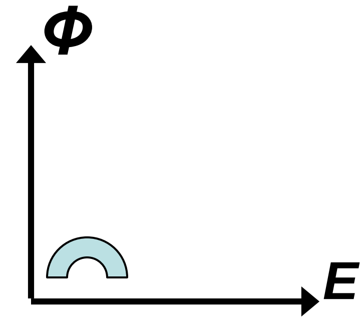
- High Energies (DIS). N.b., need νbar
  - Nuclear Effects
  - Resolving puzzles in high x PDFs
  - Strange sea



- High intensities (neutrino factory?)
  - Polarized targets for flavor resolved spin



Elastic Scattering

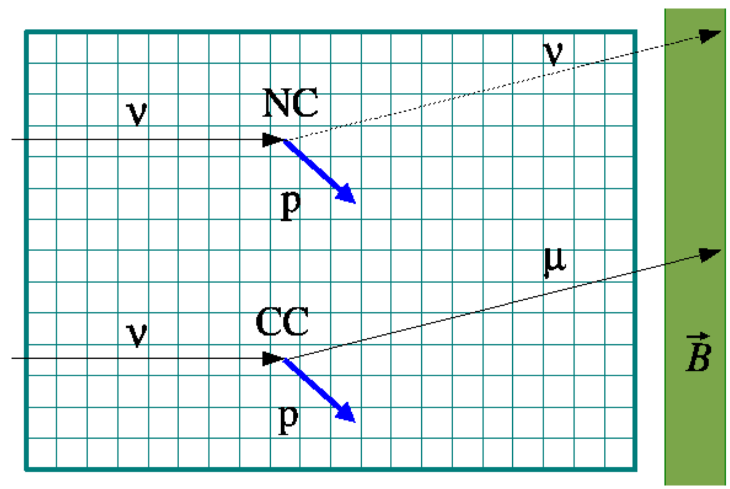


$$\frac{d\sigma(\nu N \to \nu N)}{dQ^2} \approx G_A^2$$

$$G_A(Q^2) = -\tau_z g_A(Q^2) + G_A^s(Q^2)$$

$$\tau_z = +1(p), -1(n)$$

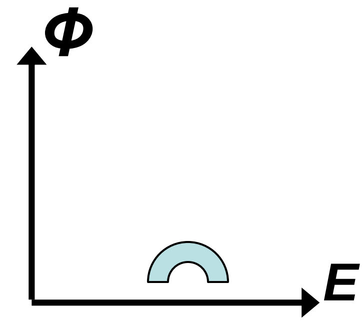
$$G_A^s(Q^2 = 0) = \Delta s$$



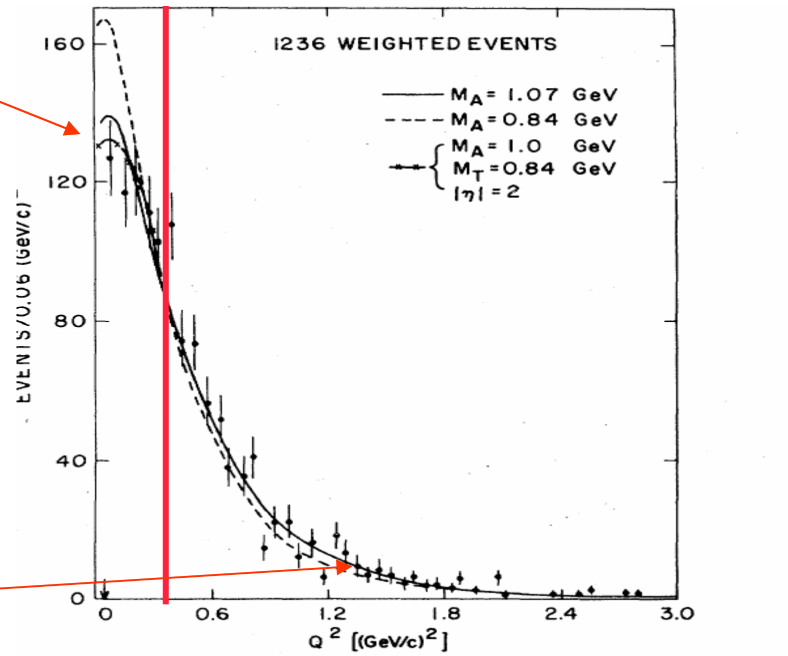
$$\frac{d\sigma(\nu p \to \nu p)}{d\sigma(\nu n \to \mu p)} \approx f(G_A^2)$$

- By measuring elastic scattering at $Q^2=0$, correct for g_A using nuclear beta decay measurements, can extract Δs
- Complimentary to other techniques for measuring strange quark spin

Quasielastic Scattering



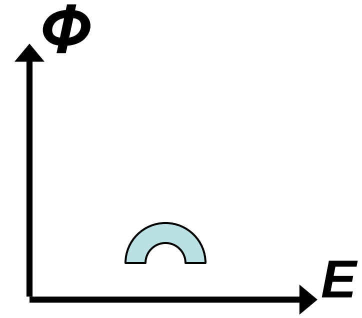
- At low Q^2, interest is testing nuclear effects measured in charged leptons and measuring "m_A"
  - "engineering"



G. 6. The Q^2 distribution for selected quasielastic ıts. The smooth line shows the best fit for $M_A = 1.07$

- At high Q^2, however, there is effectively no knowledge of form factors
  - Vector form factors not well modeled
  - If vector case is a guide, dipole approximation is wrong
  - Complimentary to JLab studies of elastic form factors

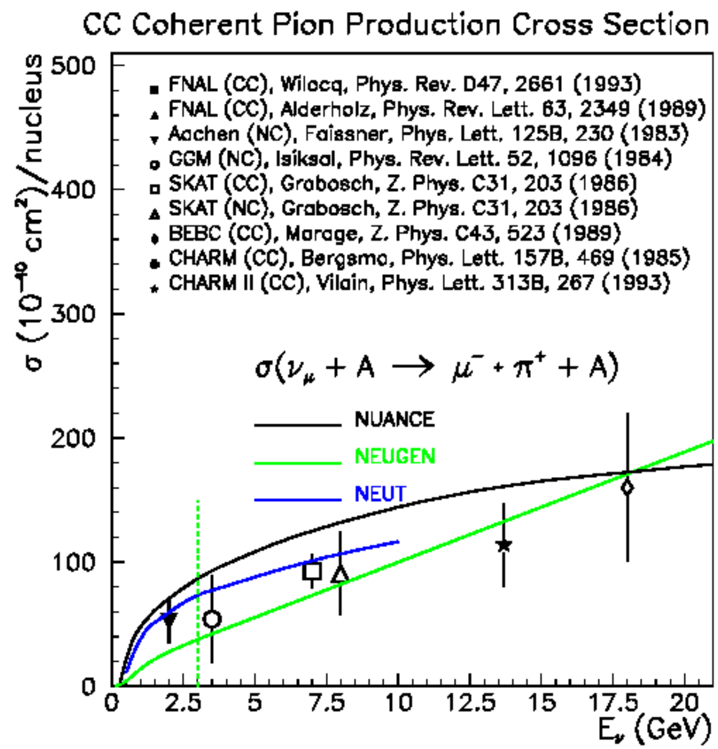
Coherent π^0 Production



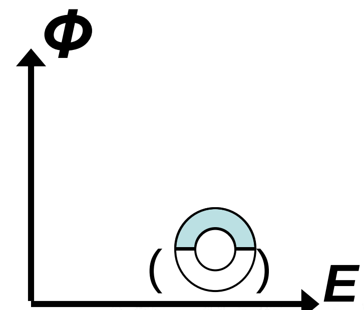
- Scatter from entire nucleus

$$\nu + A \rightarrow \nu + \pi^0 + A, \qquad \nu + A \rightarrow \mu^- + \pi^+ + A$$

- Adler's PCAC theorem: $\sigma(\nu A) \propto \sigma(\pi A)$ at $Q^2=0$
- Important background for oscillation experiments
- Signature is outgoing π^0 or π^+ at 0^o
- Strategy:
  - Measure CC process well to tune models
  - Test models with NC measurements



Resonance Production



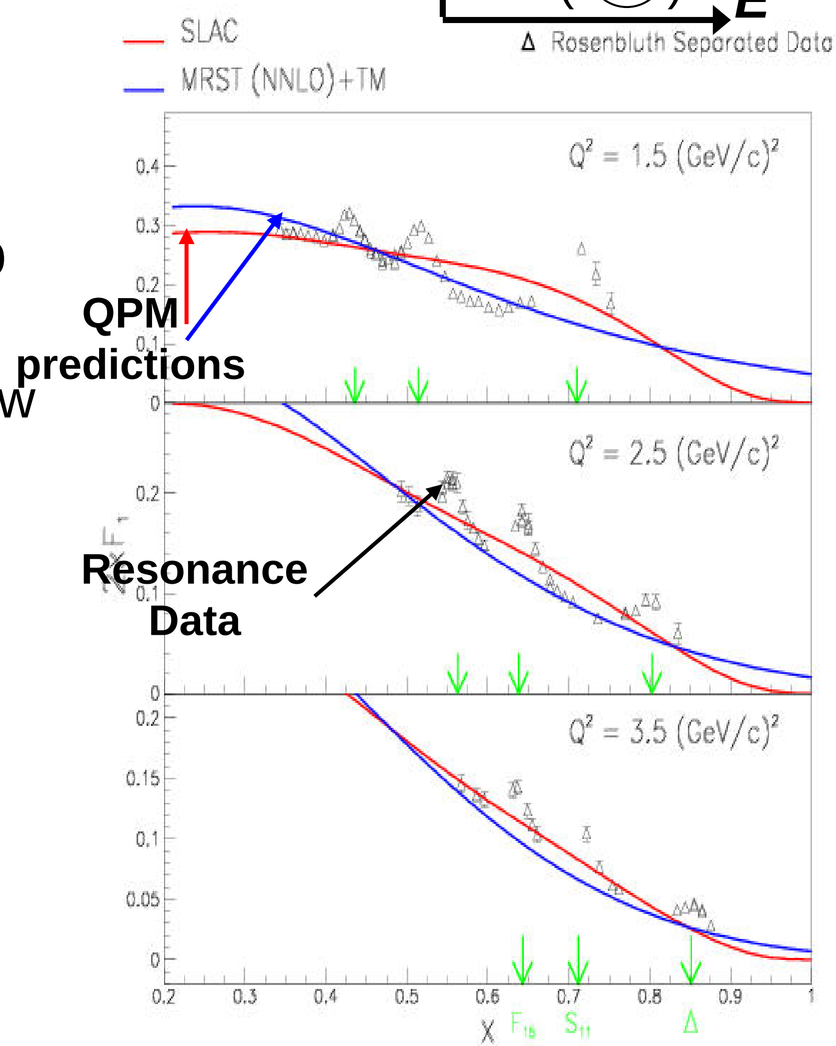
- Models now in favor (Bodek-Yang) use Bloom-Gilman duality
- Relate resonance region to QPM limit
  - "DIS with wiggles", tested now only in charged lepton NC
  - Does Bodek-Yang work in detail in neutrino scattering

$$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+$$

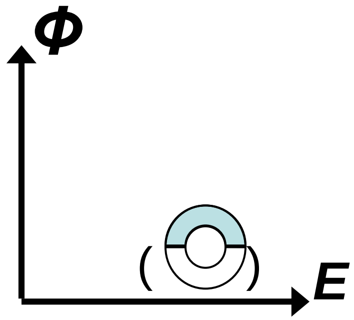
$$\nu_\mu n \to \mu^- \Delta^+ \to \mu^- n \pi^+$$

$$\nu_\mu n \to \mu^- \Delta^+ \to \mu^- p \pi^0$$

$$\nu_\mu p \to \nu_\mu \Delta^+ \to \nu_\mu p \pi^0$$

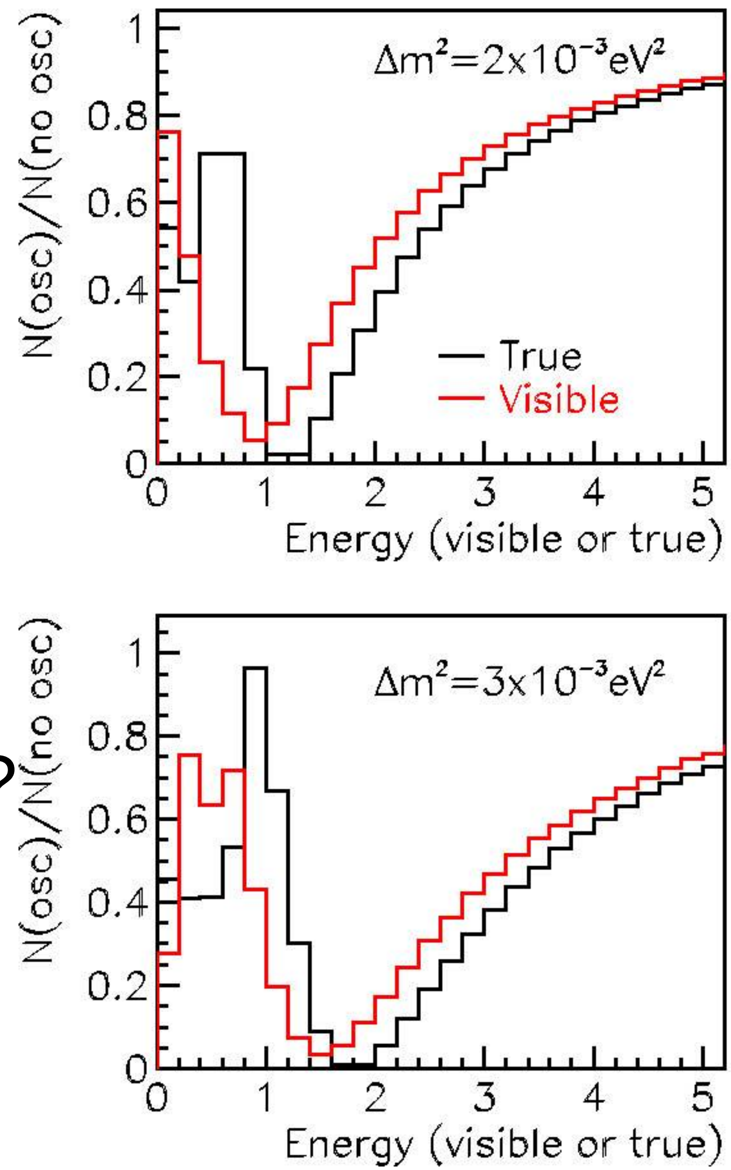


- Also relevant background for oscillation experiments

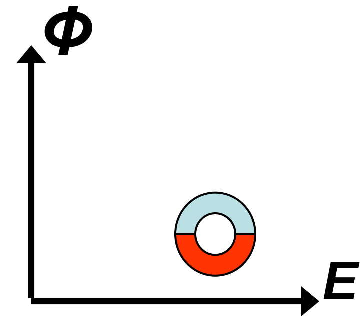


Final State Effects

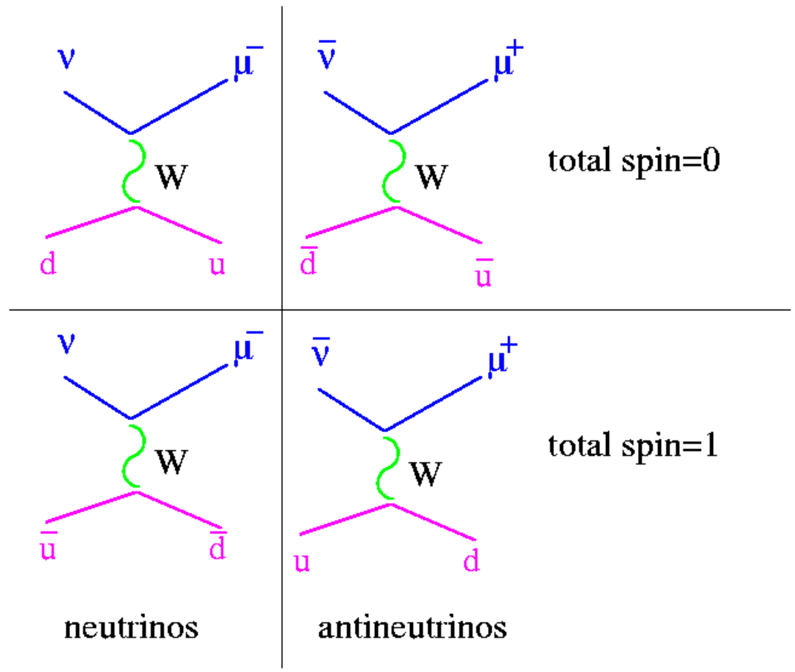
- Oscillation "engineering"
  - at low energy, visible calorimeter energy is sensitive to final state
  - important for MINOS, NUMI OA
  - How many pions produced? How many absorbed?
  - Impact on MINOS visible energy illustrated at right



PDFs in Deep Inelastic Scattering

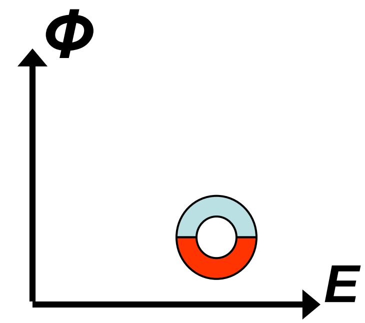


- High x parton distribution functions
  - Need ν and νbar to separate flavors

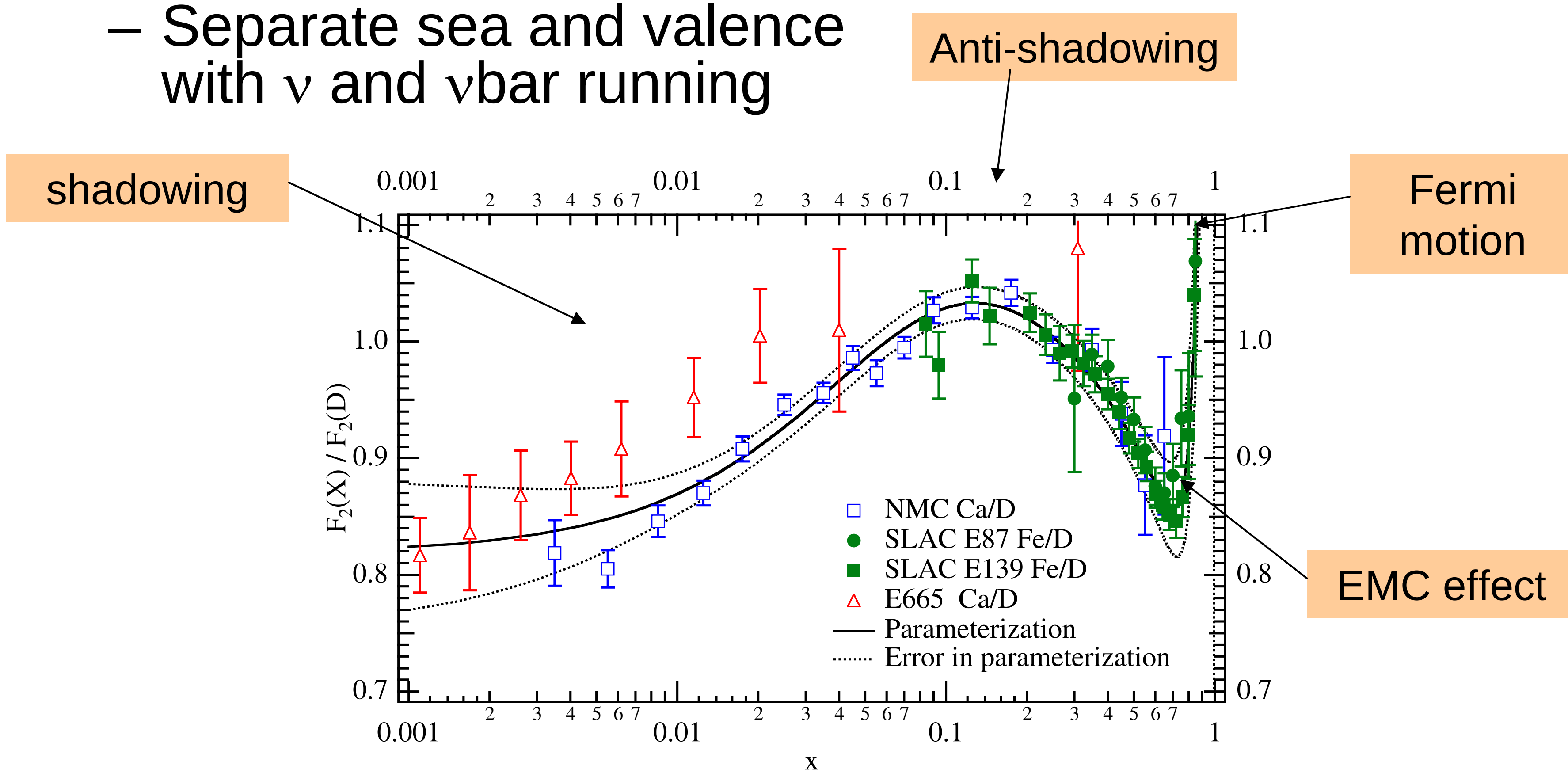


- Strange sea
  - At higher energies, neutrino CC charm production is best probe of strange sea
    - e.g., NuTeV/CCFR dimuons

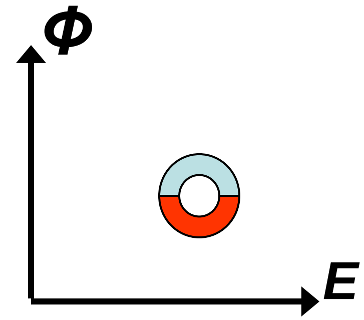
Nuclear Effects in DIS



- Well measured effects in charged-lepton DIS
  - Is the same in neutrino DIS?
  - Separate sea and valence with ν and νbar running

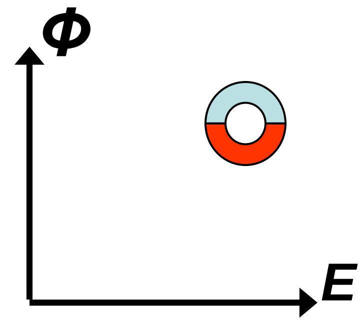


H_2 and D_2 Targets



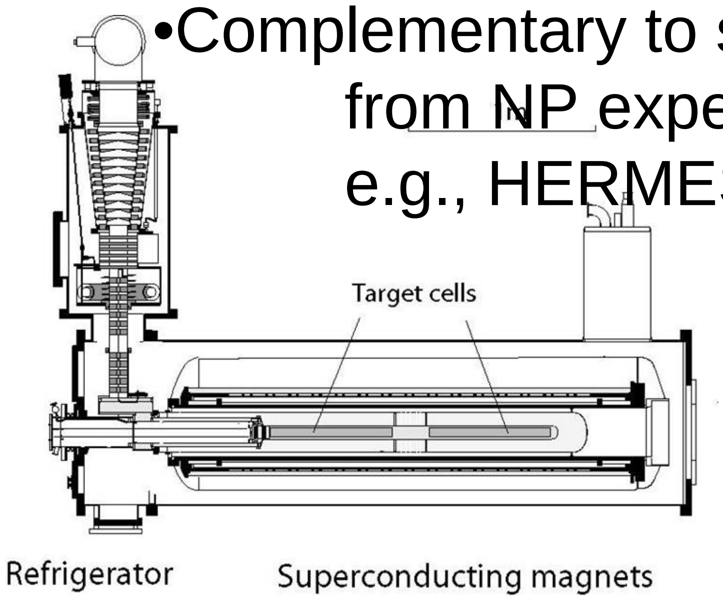
- Need High Intensity (high energy beams)
- Need ν and νbar
- New Physics capabilities
  - "clean" measurement of nucleon PDFs
    - *e.g., measurements at high x would not have uncertainty from Fermi smearing*
  - alternatively, improved "lever arm" for nuclear effects
  - isospin Violation in PDFs could be measured
    - *explicit flavor separation*
    - *experimentally viable explanation for NuTeV* $\sin^2\theta_W$

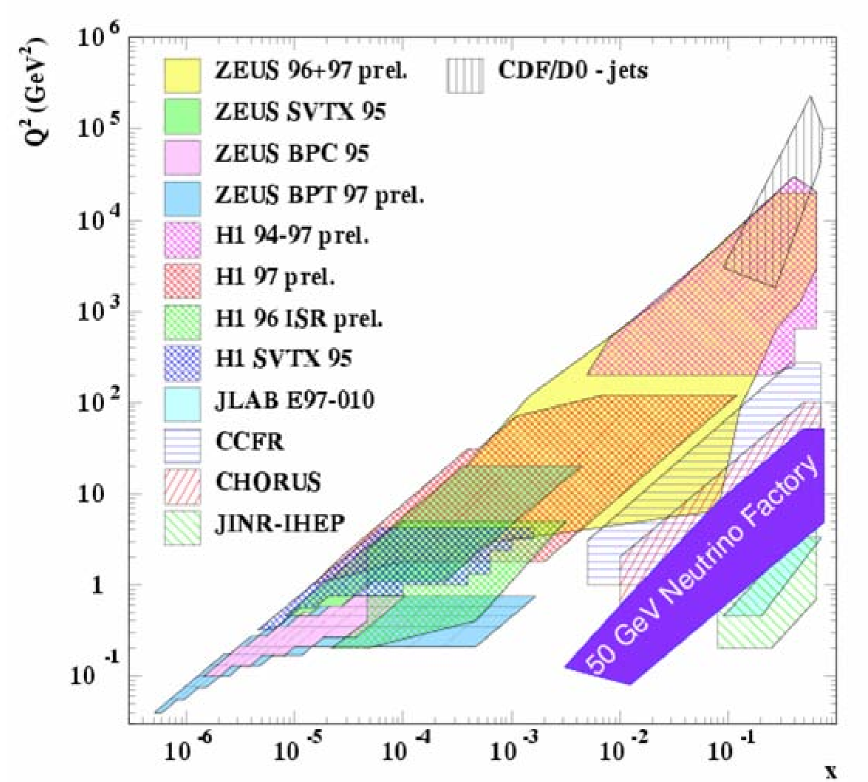
Polarized H_2 and D_2 Targets



- Need very intense beam here! (ν factory, High E)
- Flavor-dependent Spin Structure Functions

  - Isospin violation?
  - Spin contribution from strange quarks
  - Complementary to studies from NP experiments, e.g., HERMES





Some Other Excerpts of Possible Physics

Rare Processes: ν-e scattering

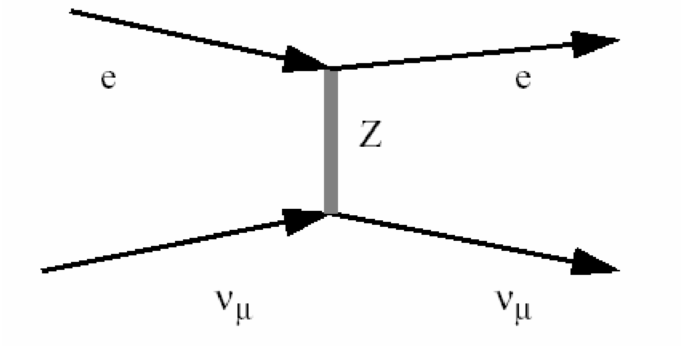
- Powerful electroweak test
  - No QCD uncertainties
  - Point-like target
  - Well-predicted σ

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right)$$

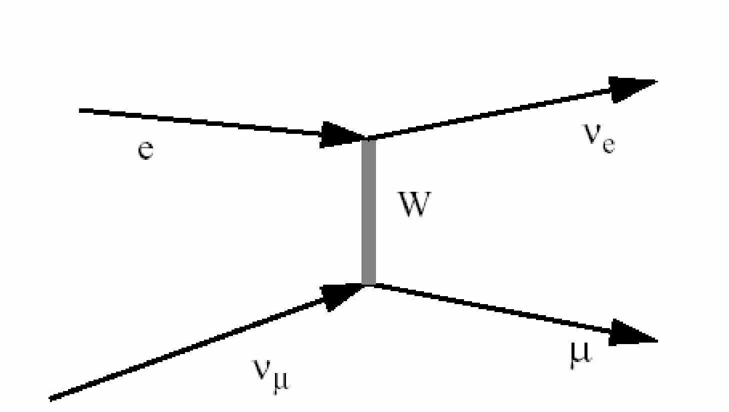
- Above 11 GeV, can normalize to CC process

$$\sigma_{TOT} = \frac{G_F^2 (s - m_\mu^2)}{\pi}$$

- Need detector with lots of background rejection for single-electron signal



$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$



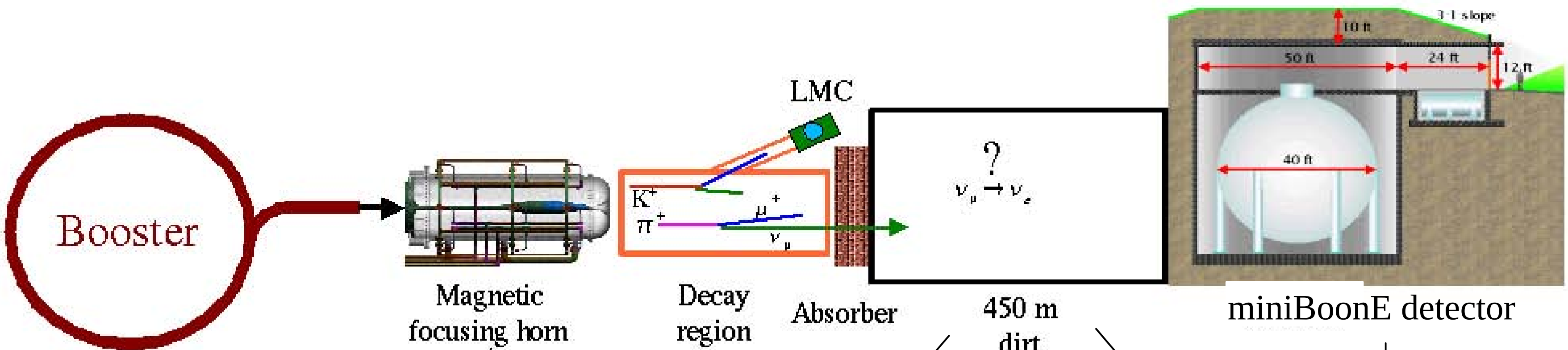
$$\nu_\mu e^- \rightarrow \nu_e \mu^-$$

BSM Physics, Examples

- Large neutrino magnetic moment
  - do high fluxes at high energy allow improvements over what can do at reactor *(this is not clear to me, although it's been discussed)*
- Spin-flavor precession
  - rare SB appearance processes *(any comprehensive studies?)*
- [Insert your favorite idea here]

Beamlines and Detectors

FNAL Booster Neutrino Beamline



horn to focus mesons towards detector

450 m baseline

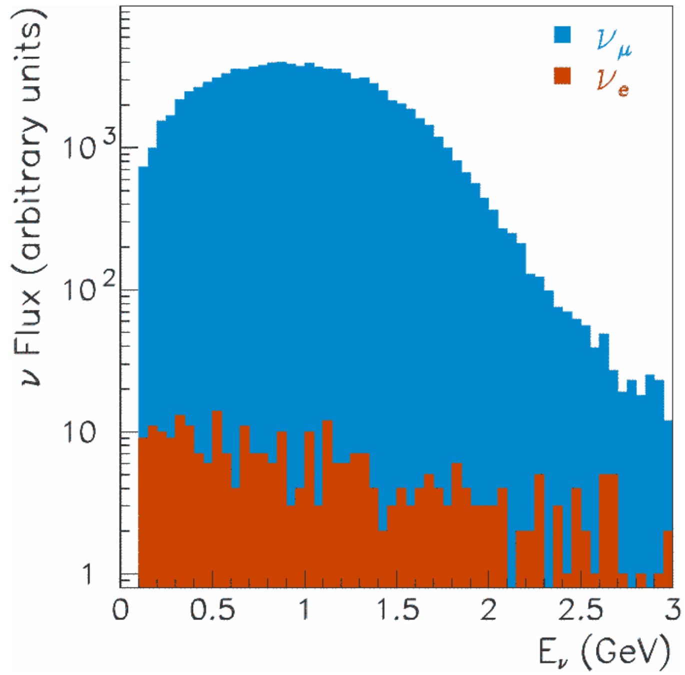
Decay region: mesons decay to neutrinos

8 GeV protons from FNAL Booster

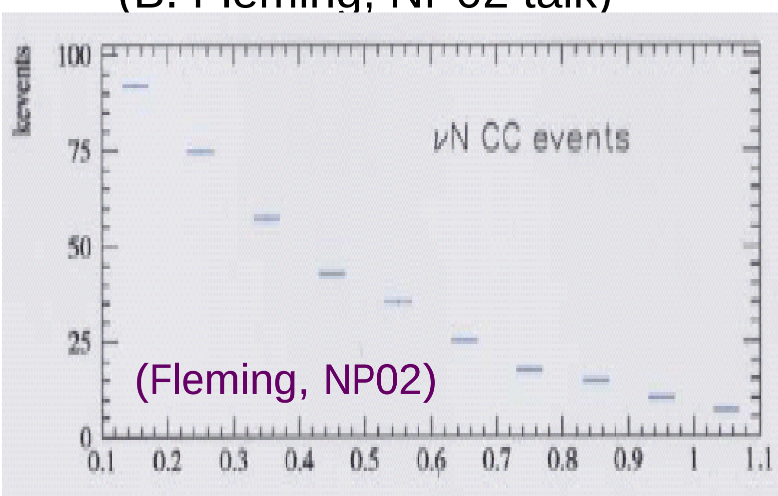
MiniBooNE detector

FINeSE at FNAL Booster

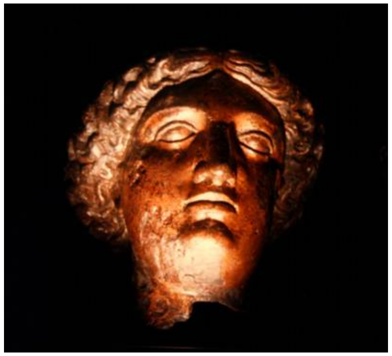
- The Beam
  - New hall 100m from Target on-axis
  - $<E_\nu>\sim 0.9$ GeV
  - 3×10^4/ton/3E20 POT



(B. Fleming, NP02 talk)

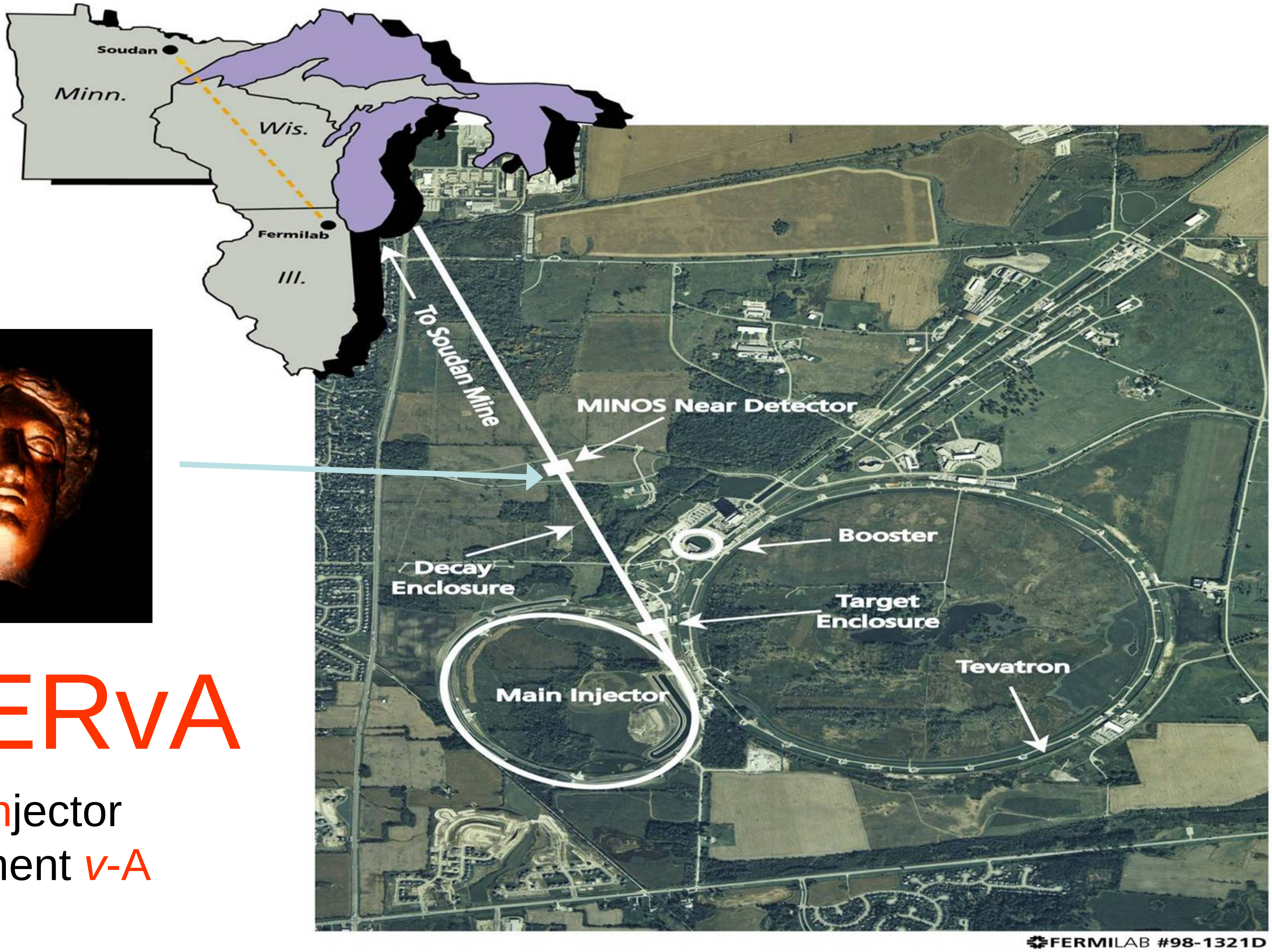


NuMI Beamline at Fermilab



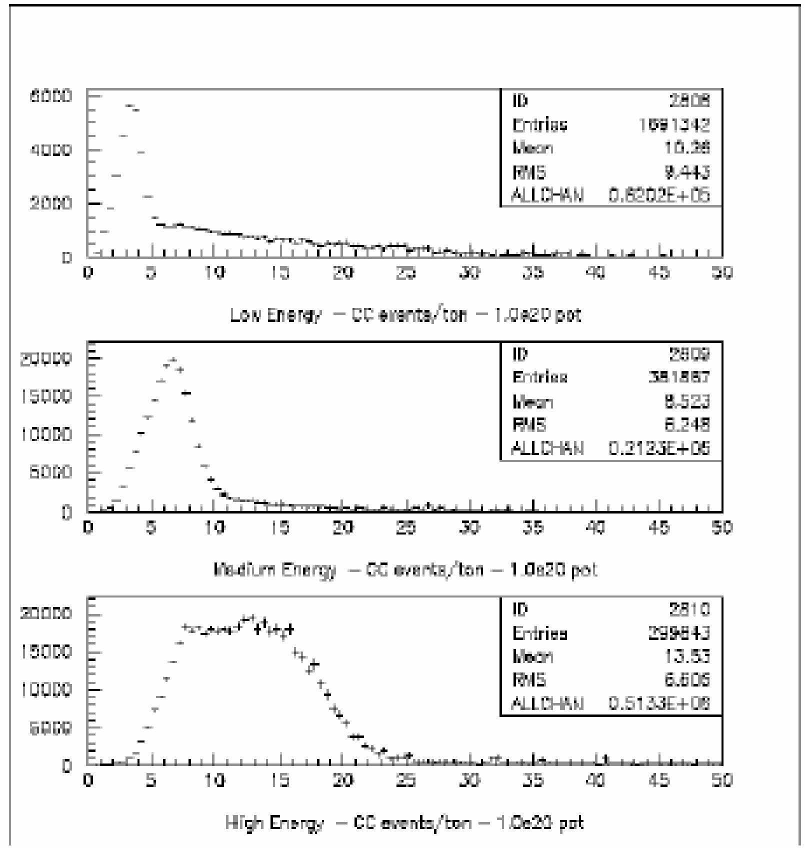
MINERvA

Main Injector
ExpeRiment *v*-A

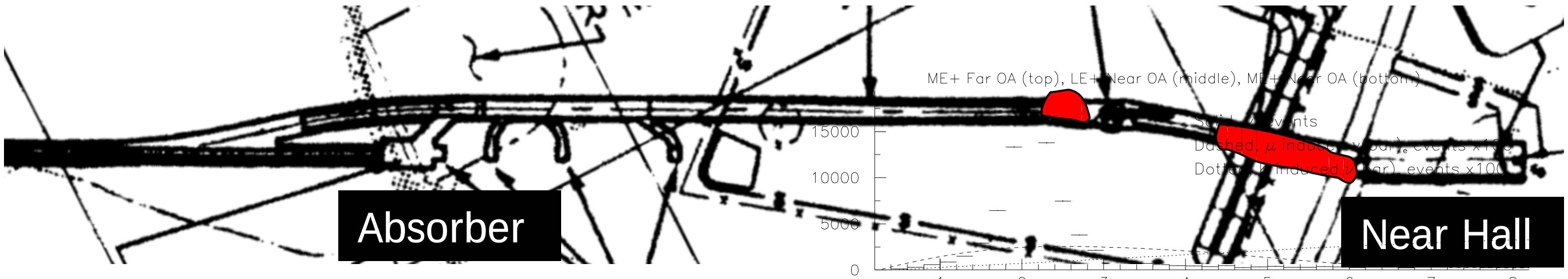


Example: Rates at NUMI Near Hall

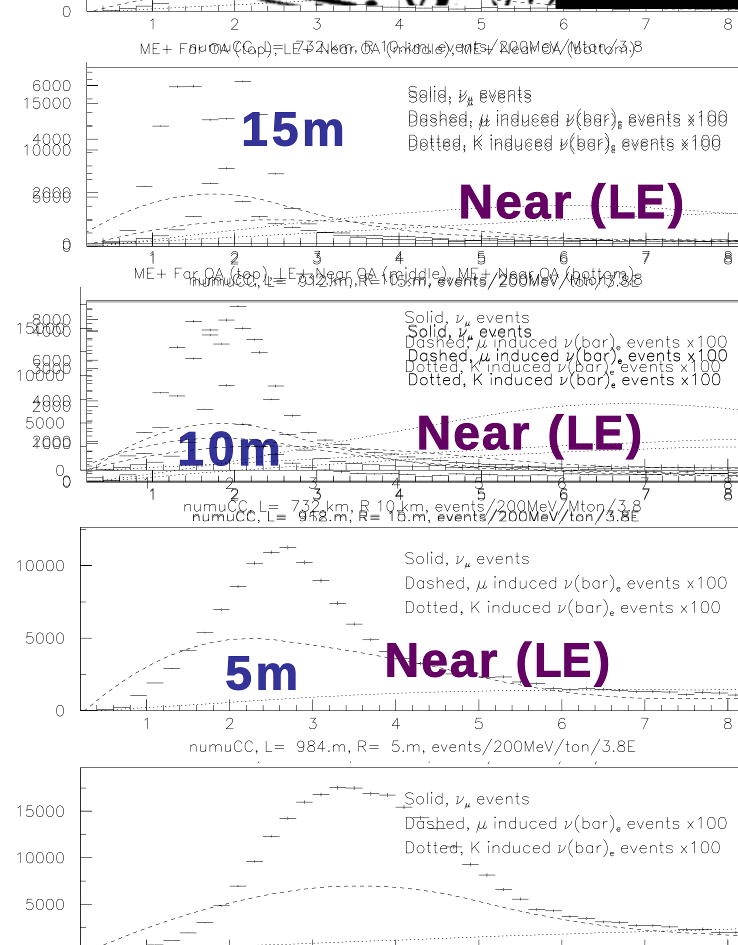
- If 2.5 x 10^{20} pot per year of NuMI running...
- Low E-configuration:
  - E_{peak} = 3.0 GeV, $\langle E_\nu \rangle$ = 10.2 GeV, rate = 2E5 events/ton - year.
- Med E-configuration:
  - E_{peak} = 7.0 GeV, $\langle E_\nu \rangle$ = 8.5 GeV, rate = 7E5 events/ton - year
- High E-configuration:
  - E_{peak} = 12.0 GeV, $\langle E_\nu \rangle$ = 13.5 GeV, rate = 16E5 events/ton - year



Easy to go 5-15 meters Off-Axis



- At NUMI, detector can be moved around to vary energy without new tunneling
- Access to lower energy beams. May be important for low energy cross-sections.



Not Your Grandfather's Neutrino Detector

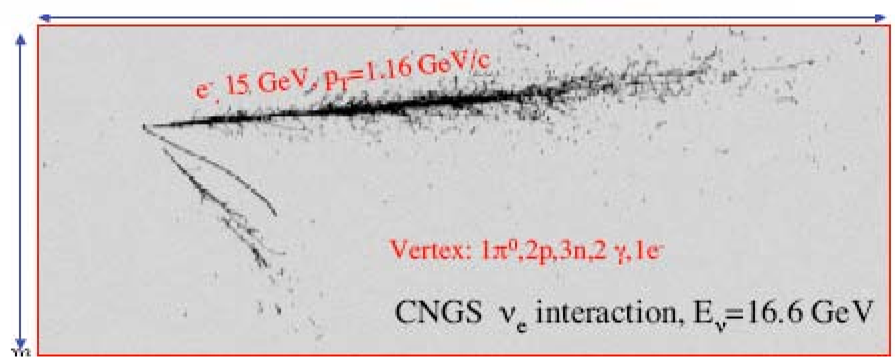
- Fluxes are high so masses can be low!

- Identification and separation of exclusive final states
  - Quasi-elastic $\nu_\mu n \rightarrow \mu^- p$, $\nu_e n \rightarrow e^- p$ - observe recoil protons
    - Implies nearly fully active – wean ourselves from sampling detectors
  - Single π^0, $\pi^\pm$ final states - reconstruct π^0
  - Multi-particle final-state resonances

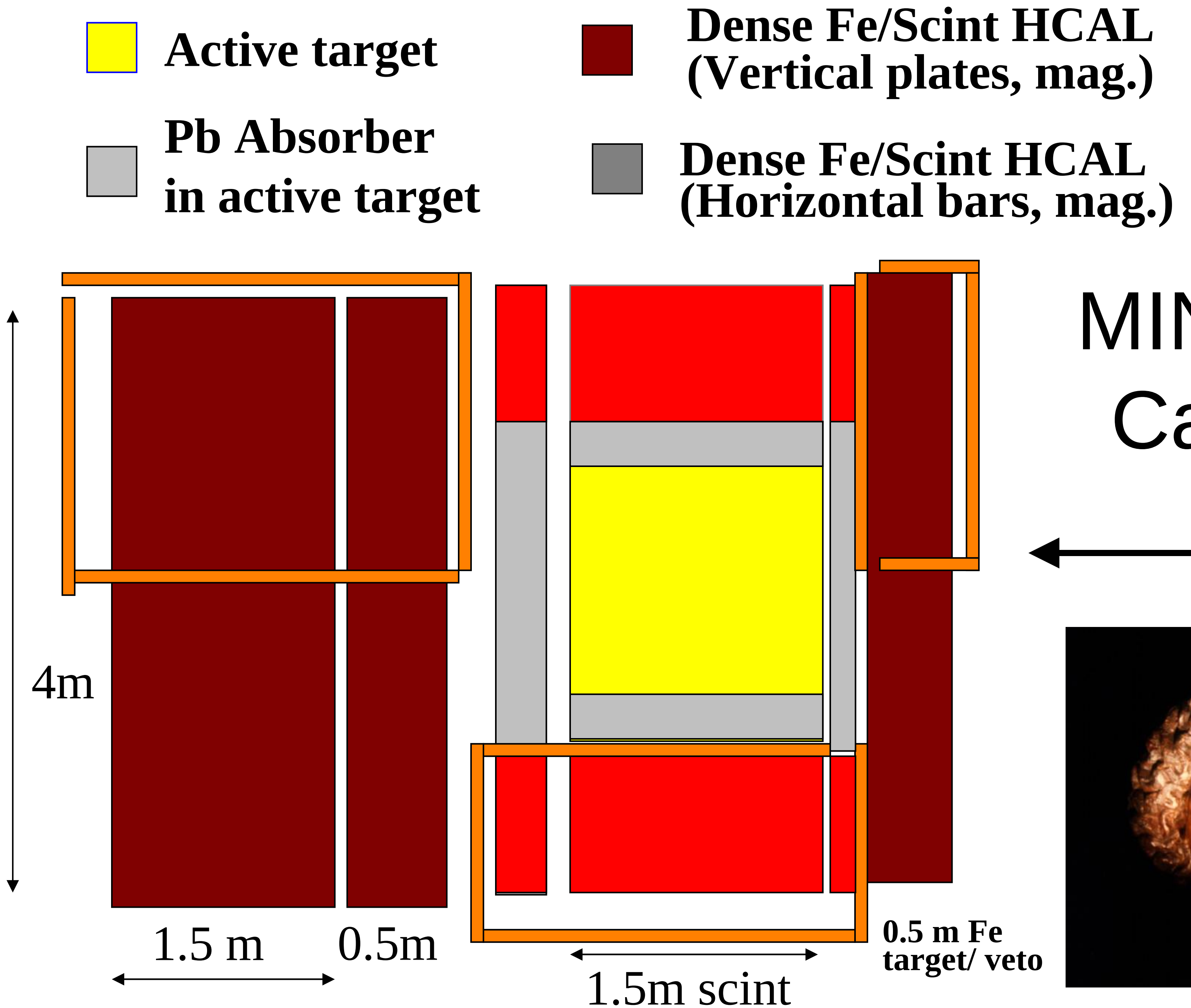
- Reasonable EM and hadronic calorimetry for DIS
  - Accurate measurements of x_{Bj}, Q^2 and W.

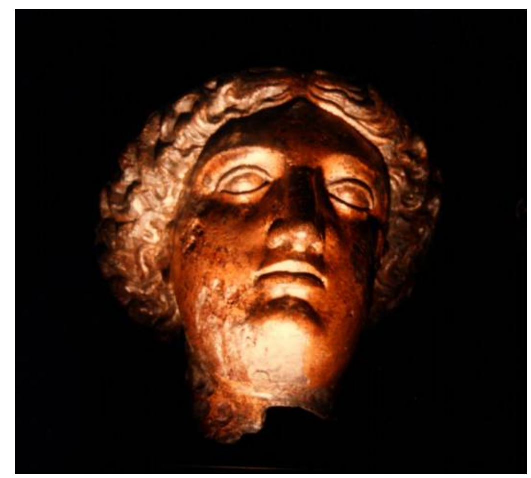
- Multiple targets of different nuclei

Liquid Argon TPC at FNAL?

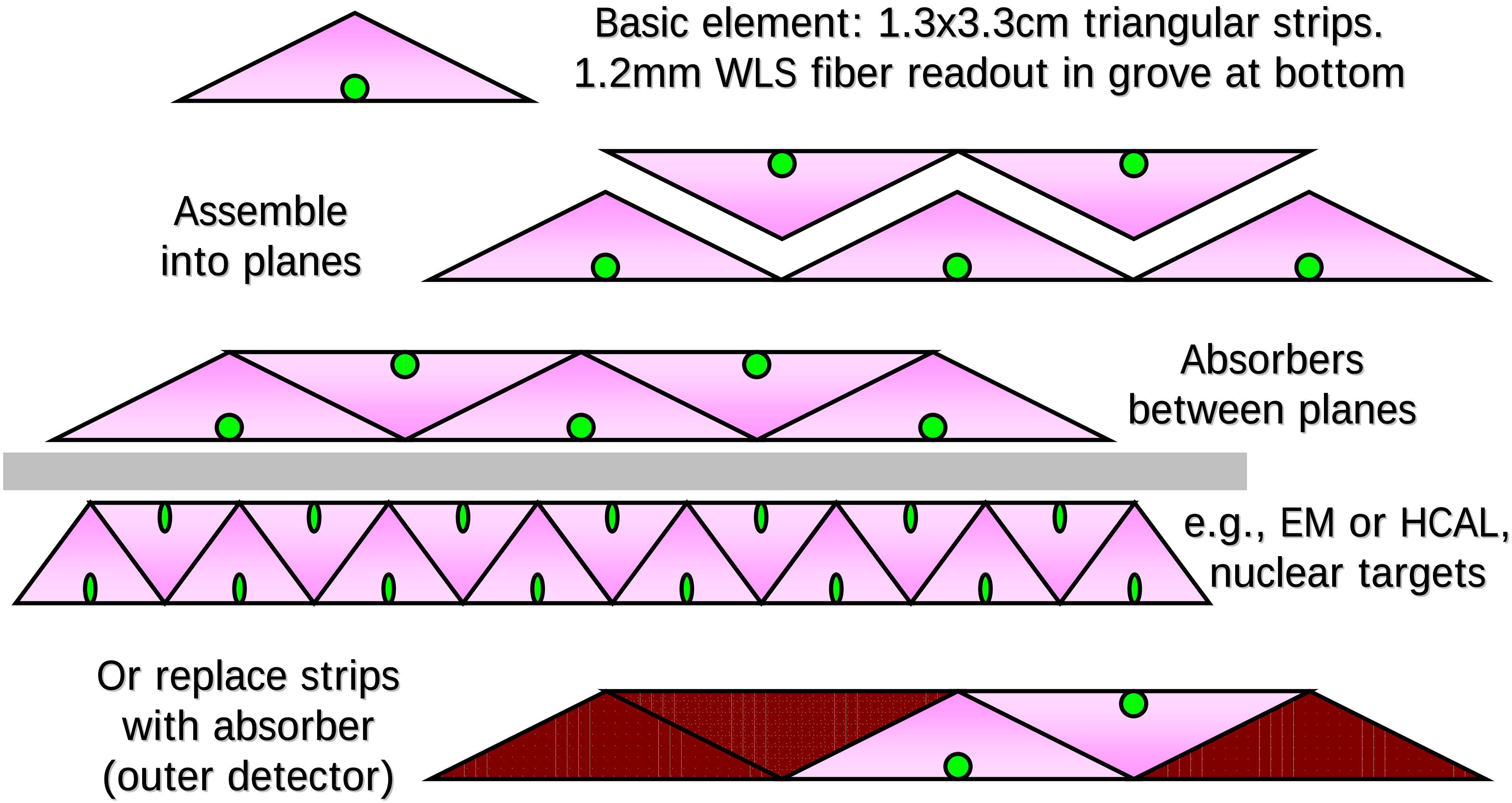


MINERvA Cartoon



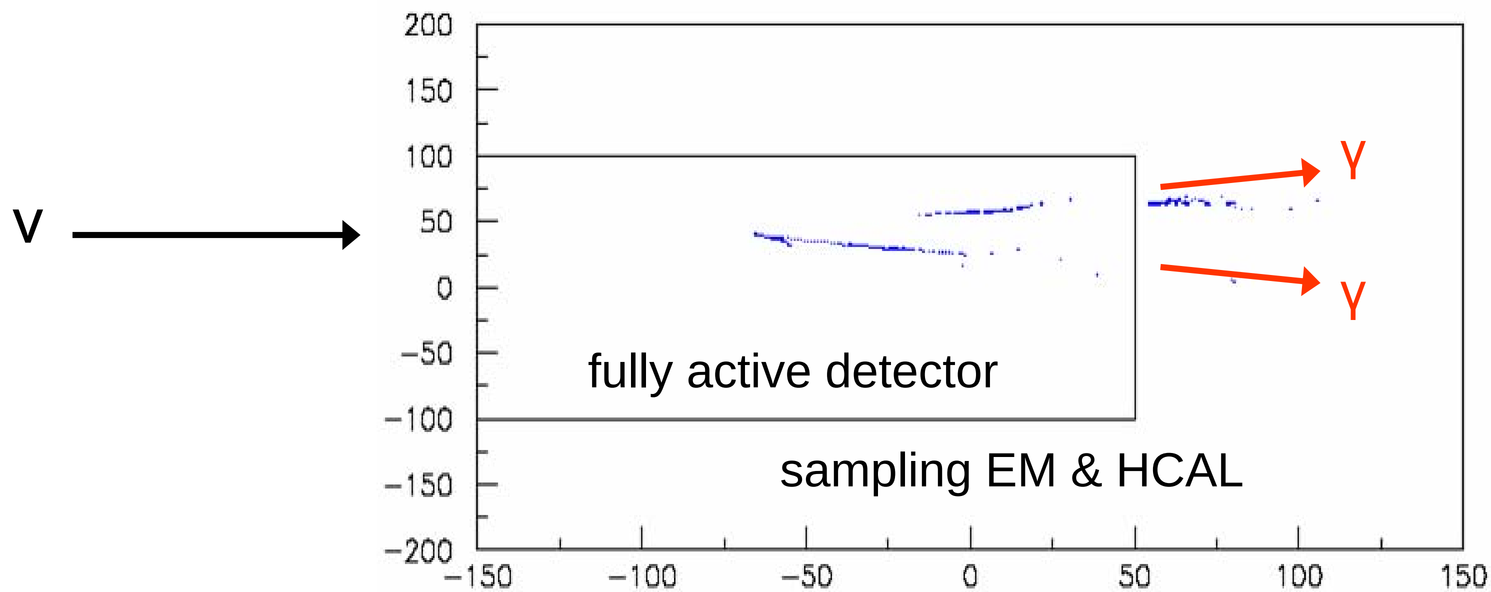


Fully-Active Detector: Extruded Scintillator



Neutrino Detectors Unbound

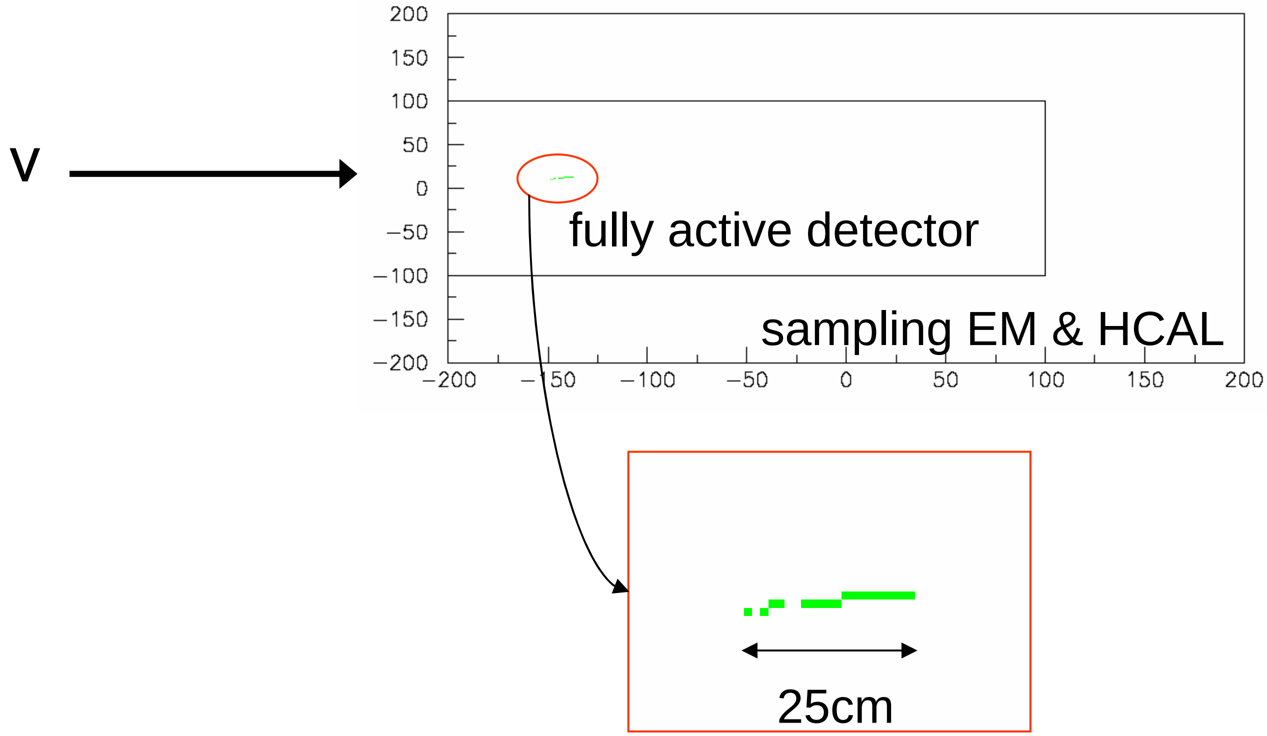
- 1 GeV coherently produced π^0
  - challenging final state to reconstruct
  - fully-active scintillator strip detector gives excellent energy, position resolution



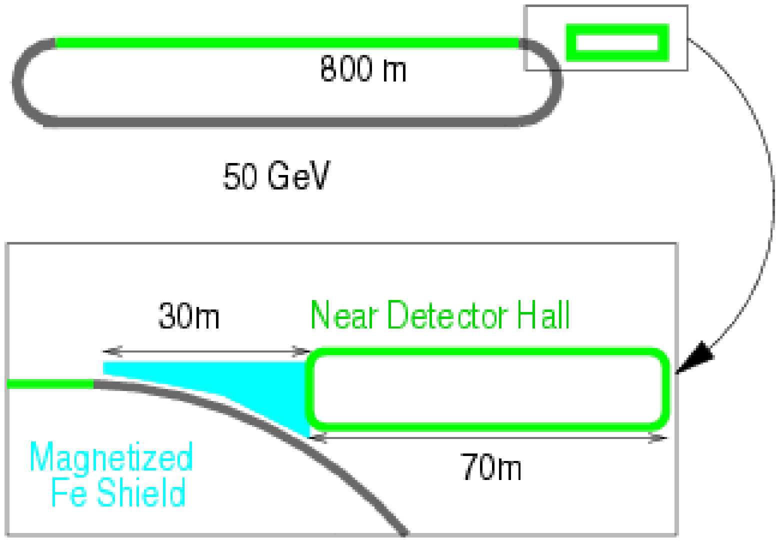
Neutrino Detectors Unbound (cont'd)

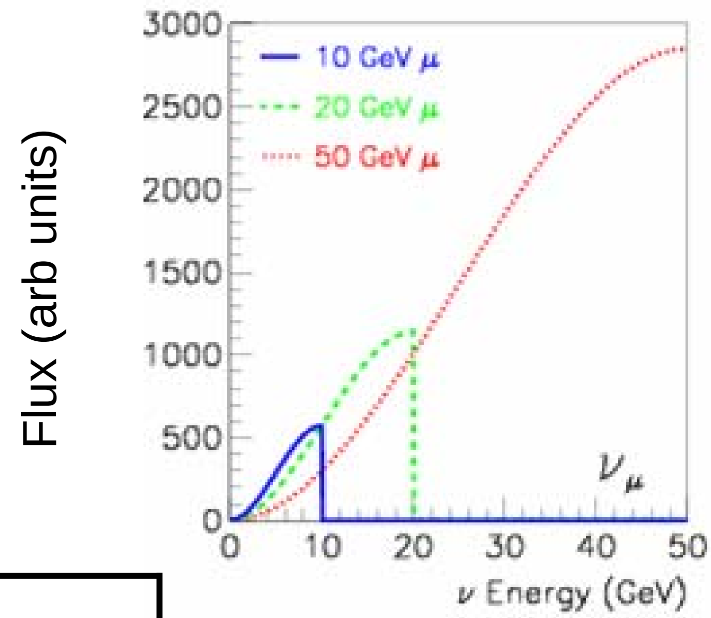
- Single proton, 200 MeV K.E. from

$$\nu_\mu p \rightarrow \nu_\mu p$$



High Rate Physics at ν Factory





Target	Thickness	Evts/$10^{20}\mu$
Liquid H_2	100cm	12.1M
Liquid D_2	100cm	29.0M
Solid HD	50cm	9.3M
C	5.3cm	20.7M
Fe	2.3cm	31.6M

Events for a 40cm Radius target… Surround with low mass Calorimetry…

Summary

- Important Physics from Low to High Energies
  - We saw, for example, how a program of QCD studies could develop with time
- Opportunistic: FNAL ν beams provide a new facility. We should exploit it.
  - "JLab" of ν. Medium energy users come to FNAL!
  - Intersection of particle and nuclear physics
- Is there new physics to be found?

- Oscillation Physics needs these measurements

A Possible Recommendation

"Existing and planned neutrino beams at Fermilab provide unprecedented new opportunities in high rate neutrino physics.

A modest investment in new near-source detectors will be repaid handsomely in new physics from FNAL and new physicists attracted to FNAL.

We encourage cooperation between the HEP and NP communities in planning the exploitation of this resource."